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The amplification of Arctic terrestrial surface temperatures by reduced sea-ice extent during the Pliocene

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ABSTRACT

Many past warm periods exhibited greatly reduced latitudinal temperature gradients as a result of amplified Arctic surface temperatures as well as more seasonably equable temperatures. The Pliocene is a period of particular interest because CO_2 forcing was comparable to today and yet Arctic temperatures were significantly warmer than today. Here we describe an atmospheric general circulation model experiment assessing the response of terrestrial temperatures in the mid-Pliocene (3.02 to 3.26 Ma) to an ice-free Arctic, and we compare the simulation with a compilation of proxy-based Pliocene paleotemperature reconstructions. Our experiments indicate that the amplification of Arctic surface temperatures is much more sensitive to the extent of sea ice than continental ice. The removal of Arctic sea ice results in simulated mean annual surface temperatures that better match terrestrial proxy data (RMSE = 2.9 °C) than experimental conditions that included seasonal sea ice (RMSE = 4.5 °C). Our simulations also show a decrease in the seasonal amplitude of temperatures in the absence of sea-ice, which is consistent with theory predicting more equable climates in the Arctic during warmer intervals in Earth's history. Our results demonstrate that once sea-ice is removed, latent heat is lost from the ocean to the atmosphere as water vapor that can be circulated by the atmosphere, which results in warming of continental interiors. Although our sensitivity experiment does not help to identify the full array of feedback mechanisms responsible for the amplification of Arctic surface temperatures during the Pliocene, it does demonstrate that Arctic terrestrial surface temperatures are extremely sensitive to the spatial and seasonal extent of sea-ice.

1. Introduction

At present, Arctic surface temperatures are increasing at approximately twice the rate of global surface temperatures (ACIA, 2005). It is well documented that Arctic temperatures of the past have been amplified relative to global surface temperatures, such that Arctic surface temperatures tend to be 3 to 4 times cooler during glacial intervals and 3 to 4 times warmer during past warm intervals (Miller et al., 2010). In fact, over much of the Cenozoic era the Arctic has been considerably warmer than present (Greenwood and Wing, 1995a, 1995b; Sluijs et al., 2006; Ballantyne et al., 2010; Eberle and Greenwood, 2011). Although general circulation models tend to be accurate at hindcasting low-latitude temperatures during past warm intervals they tend to underpredict high-latitude temperatures, especially in the Arctic, during past warm intervals (Huber, 2008; Shellito et al., 2009; Melles et al., 2012). This consistent under-prediction of Arctic surface temperatures by coupled atmosphere–ocean GCMs (AOGCMs) may result from uncertainties in prescribed forcings and boundary conditions, or may suggest that the models do not yet incorporate the full array of positive feedback mechanisms required to amplify Arctic surface temperatures. Thus the inability of models to capture the amplification of Arctic temperatures during past warm intervals calls into question their reliability in predicting future warming in response to anthropogenic greenhouse gas emissions (Sloan et al., 1996; Lunt et al., 2009a, 2009b; Shellito et al., 2009; Pagani et al., 2010; Melles et al., 2012). However, very little is known about boundary conditions in the Arctic during the Pliocene and thus the accuracy of model predictions may be limited by boundary conditions that are poorly-constrained by observations (Dowsett and Robinson, 2009).

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In order to reconcile the extreme Arctic warmth indicated by paleo-proxy data with the modest Arctic warmth indicated by AOGCM simulations of past climate, several feedback mechanisms involving the ocean, atmosphere and cryosphere have been hypothesized. It has been suggested that the amplification of Arctic temperatures may be due to increased pole-ward heat transport by the oceans (Dowsett et al., 1992) and that changes in the bathymetric boundary conditions of the North Atlantic may have allowed for this increased pole-ward heat transport by the oceans (Robinson et al., 2011). Although this feedback mechanism based on ocean dynamics is compelling, it has been demonstrated that fully coupled climate models with the greatest amount of Arctic amplification show only a slight increase, or even a decrease, in total pole-ward energy transport (Hwang et al., 2011). Nonetheless, results from Robinson et al. (2011), suggest that even slight changes in model boundary conditions can result in large effects on the radiative budget of the Arctic. It has also been proposed that enhanced cloud formation, particularly stratospheric clouds during winter months, may result in the amplification of Arctic surface temperatures (Sloan and Pollard, 1998). More recently it has been suggested that in an ice-free state there is an increase in atmospheric convection over the Arctic Ocean resulting in greater atmospheric water vapor and cloud formation, which thereby causes radiative warming of the surface that has the potential to maintain the ice-free state (Abbot and Tziperman, 2008). Probably the most potent feedback mechanism with the greatest potential for amplifying Arctic surface temperatures in the past is the ice-albedo effect over the Arctic Ocean (Miller et al., 2010). Sea ice covered in snow reflects nearly 90% of the sun's energy (albedo ~0.9), whereas the open ocean absorbs nearly the same amount of energy (albedo ~0.1). Thus any warming that results in a loss of sea ice is enhanced by the strongly positive ice-albedo feedback. It is unlikely that any single feedback mechanism can explain the full magnitude of Arctic amplification occurring in the past, but rather the interaction of feedback mechanisms within the ocean, atmosphere, and cryosphere is most likely necessary to explain the amplification of Arctic surface temperatures.

Most of the past warm intervals in Earth's history are characterized by a reduced equator-to-pole temperature gradient, but another common feature of most past warm intervals is the reduced amplitude of seasonal surface temperatures. This so-called 'equable' climate regime has been identified in Arctic climates of the past (Greenwood and Wing, 1995a, 1995b), but has puzzled climate scientists seeking physical mechanisms to explain the persistence of the equable climate regime over much of the Cenozoic (Farrell, 1990). In fact, recent paleoclimate reconstructions from Greenland indicate a general cooling trend from the Eocene (~50 MYA) through the Oligocene (~30 MYA), but that most of this cooling is due to a decrease in the cold month mean temperature (CMMT), suggesting the emergence of greater seasonality as the Arctic cooled (Eldrett et al., 2009). This trend of increasing seasonality appears to extend through the Pliocene and into the Pleistocene as evidenced by a greater change in CMMT than warm month mean temperature (WMMT) as inferred from fossil beetle assemblages in the Arctic (Elias and Matthews, 2002). Therefore the net effect of physical mechanism invoked to explain the amplification of Arctic surface temperatures during past warm intervals must also result in the reduced seasonality characteristic of more equable climates.

The Pliocene epoch represents an excellent test-bed for exploring feedback mechanisms driving warm and equable Arctic surface temperatures and possibly the most relevant analog for the equilibrium climate response to future anthropogenic warming. Mid-Pliocene atmospheric CO_2 concentrations were likely within 40 ppmv of present-day values (Kurschner et al., 1996; Raymo et al., 1996; Pagani et al., 2010) and Pliocene continental configurations were broadly similar to today. Although the Central American and Indonesian seaways may have remained slightly open during the mid-Pliocene, evidence suggests that they were greatly constricted and their impact on ocean heat transport was greatly diminished by 4 Ma, suggesting that ocean circulation patterns were very similar to modern patterns (Haug and Tiedemann, 1998; Karas et al., 2011). Paleotemperature proxies indicate that globally averaged mean annual temperatures (MAT) were 2 to 4 °C warmer than present-day, but proxy estimates from the Arctic suggest that temperatures were 10 to 20 °C warmer than present-day (Dowsett, 2007; Salzmann et al., 2008; Robinson, 2009; Ballantyne et al., 2010). Forests extended to the Arctic Ocean, nearly eliminating the Arctic tundra biome (Salzmann et al., 2008), and global sea level reached 22 ± 10 m higher than present (Miller et al., 2010). Although proxy data clearly show a reduced latitudinal temperature gradient and a reduced amplitude of seasonal temperatures in the Pliocene Arctic, this pattern of amplified Arctic surface temperatures and more seasonally equable climates has proven difficult to simulate with coupled AOGCMs (Sloan and Rea, 1995; Dowsett et al., 1996, 2012a, 2012b; Lunt et al., 2009a, 2009b). Thus it is clear that model–data mismatch in the Pliocene Arctic may be due to known unknowns such as uncertainties in forcings and boundary conditions, or possibly missing feedback mechanisms that may amplify Arctic surface temperatures.

Although considerable effort has been invested in characterizing the climate and boundary conditions of the Pliocene, very little is known about climate conditions over the Arctic Ocean during the Pliocene. The U.S. Geological Survey's recently updated Pliocene Research, Interpretation and Synoptic Mapping (PRISM3D) project has synthesized reconstructions of middle Pliocene (3.02 to 3.26 Ma) sea-surface temperatures, ocean bottom-water temperatures, sea level, topography, vegetation cover, land ice and sea ice extent (Dowsett et al., 2010). Although PRISM3D constitutes the most complete global paleoclimate reconstruction available for any pre-Quaternary time period, dates of proxy data are poorly constrained making it difficult to resolve orbital climate variability, such as changes in Earth's obliquity (41,000 yr^{-1}) that are known to have been operating during the Pliocene (Ravelo et al., 2004). However, climatic conditions over much of the Arctic Ocean remain poorly constrained due to a lack of proxy data estimates of sea surface temperature or sea-ice extent. The few available reconstructions of Pliocene sea-surface temperatures in the northernmost North Atlantic and the marginal Arctic Ocean indicate warm temperatures consistent with at least seasonally ice-free conditions (Brigham-Grette and Carter, 1992; Cronin et al., 1993; Robinson, 2009), but there are no direct reconstructions of Pliocene sea-ice persistence or extent in the Northern Hemisphere. Confronted with the paucity of proxy data alongside the need to specify sea ice extent for the Pliocene, workers developing the PRISM3D boundary conditions assumed a fairly conservative sea ice extent, with an ice-free Arctic Ocean in summer, and winter sea ice conditions approximately equivalent to modern summer ice extent (Dowsett et al., 2010). However, large uncertainties regarding the seasonal distribution and spatial extent of Pliocene sea ice remain, representing a critical unknown boundary condition for climate simulations of the Pliocene — a critical interval in Earth's history for validating climate model skill at predicting surface temperatures, especially in the Arctic.

Here we report the findings from a simple climate experiment to assess the sensitivity of Arctic terrestrial surface temperatures to the presence of Arctic sea ice during the Pliocene. We conducted two atmosphere-only GCM (AGCM) experiments of Pliocene climate. The first experiment used the conservative estimate of sea-ice boundary conditions from PRISM3D; the second removed all sea and continental ice from the Arctic. We then compared these two climate simulations with circumpolar proxy data representing terrestrial surface temperatures from the Arctic during the Pliocene. In particular, we evaluated the effectiveness of our climate simulations at hindcasting the reconstructed Pliocene equator-to-pole temperature gradient over continental regions. We also evaluated the models' ability to hindcast the MAT, CMMT and WMMT recorded in proxy data and thus their ability to capture the more equable seasonal cycle. Lastly, we used the model simulations to explore possible feedback mechanisms that may account for the